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Interactions between China's economy, energy and the air emissions and their policy implications

XiaoHong Zhang *, He Hu, Rong Zhang, ShiHuai Deng

Department of Environment Science & Engineering, College of Resource and Environment, Sichuan Agricultural University-Chengdu Campus, Chengdu, Sichuan 611130, PR China

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ABSTRACT

How to coordinate the relationships between economy, energy and environment is a complex issue for China. This paper presented an indicator system based on energy, emergy and monetary units to explore the interactions between China's economic growth, its energy production and consumption, and the related air emissions during 1995–2011. The results show that (1) China's energy utilization efficiency is continuously raised whilst the total production efficiency is just slightly improved; (2) petroleum import has surpassed international warning line (50%) since 2007, and it is further challenging China's energy security; (3) basic energy mix is still mainly composed of coal and petroleum; (4) air emissions' impact from energy production has climbed rapidly whilst that from energy consumption has declined slowly. Air emissions' impact from energy consumption still has main contribution to the total emissions' impact whilst that from energy production has an increasing share. Therein, air emissions' impact mainly comes from the impact on human health. While air emission intensity from energy consumption decreases obviously, that from energy production generally increases; (5) generally, the relationships between the structures of economy and energy and air emissions have become more coordinated. Compared with structure coordination degree, the improvement of scale harmony degree between the three aspects is much slower due to rebound effect, which will seriously challenge the presented targets in 12th Five-Year-Plan (FYP). Promoting the synergistic effect should become the underlying strategy for future economic sustainable development.

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* Corresponding author. Tel.: +86 28 86291390; fax: +86 28 86291132.
E-mail address: zxh19701102@126.com (X. Zhang).

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1. Introduction

China's economy has been growing by 11.25% of GDP or 10.11% of per capita GDP during 1978–2011 (Fig. 1). And even the world financial crisis began in 2008 has not stopped the pace of China's economic growth. The country's economic miracle has induced huge energy consumption and serious air environmental pollution. China is a dominant energy consumer in global context [1], and its primary energy consumption has exceeded domestic energy production since 1994, leading to a substantial expansion in energy imports, particularly of oil. China's energy demand has an increasingly significant impact on global energy markets [2]. At present, China has the greatest contribution to SO_2 and CO_2 emissions in the world [3]. With the continuing growth of economy in the next 10–15 years, China will face a more severe situation of energy consumption and the related increasing multiple pollutant emissions. Regional air pollution especially fine particles and ozone from fossil fuel consumption has not been well solved for the country [4], which contributes greatly to the burden of disease [5]. Meanwhile, the increasingly serious global climate change issue has and will become another challenge for China's future energy development [6], and emissions of greenhouse gases from energy use will inevitably intensify China's environmental health troubles. Therefore, the Chinese government has to take measures to improve the environmental efficiency and restructure the economic growth pattern [7].

China's economic growth needs lots of energy to support, but how to obtain a sufficient energy supply is now a problem. Meanwhile, environmental pollution caused by energy production and consumption is a problem that urgently needs to be solved [7] because ambient air pollution had diverse negative effects on human health [8]. And these issues have inspired many related researches, such as energy and environment [1,9–16], energy and economy [17–19], energy and exports [20–25]. But those existing researches only focused on one or two aspects of China's economy–energy–environment related issues and could not give full perspectives to decision-makers. Recently, some researches also began to address economy and energy and environment related issues of China [26–32]; however, air emissions' impact from energy production and/or other air emissions besides CO_2 have not been fully considered in those researches. The relationships between economy, energy and environment are very complicated, and exploring these complex issues needs a systematic tool in order to consider the related issues from different angles as well as an integrated level. Maybe integration of different measurement tools is one of the solutions.

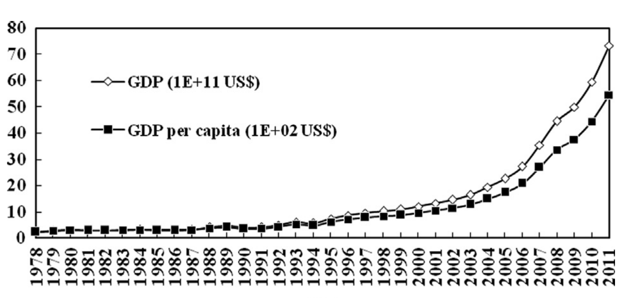

Fig. 1. Trends of GDP and per capita GDP of China during 1978–2011 (from this study).

Therein, emergy can act as one of the measurement tools. Emergy is defined by Odum as the sum of the available energy (exergy) of one kind previously required directly and indirectly to make a product or service [33]. This method has been widely accepted as an effective ecological evaluation tool to assess comprehensive performances of all kinds of systems with different scales and functions [34–78]. Recently, emergy approach has been also improved by some scholars, including improving its accounting [79–85], quantifying impact of emissions in terms of emergy [86,87], measuring environmental carrying capacity in terms of emergy [88], updating some of the unit emergy values [65,89,90], joint use of emergy approach and other methods [68,82,85,91,92], etc. However, it is still necessary to further extend the research fields of emergy approach in order to fully explore its potential, such as emergy analysis of the performance of national energy production and consumption, emergy evaluation of the relationships between one country's economy and energy and emissions, etc. Of course, more other measurement tools and methods, such as economic measurement, energy measurement, etc., could be combined with emergy to set up the corresponding indicator system so as to assess this complex system from different angles and holistic levels simultaneously.

China has attracted worldwide attention due to its global economic and environmental effects derived from its rapid economic growth over the last 30 years, with particularly concerning about its accelerating energy consumption and resulting air emissions. China is facing severe energy-related challenges that conflict resource shortages with the planned rapid economic growth, energy use with the related air pollution, and new technology with the old production/consumption patterns. It is recognized that energy development must follow a sustainable path to coordinate economy growth, social development, and environmental protection [93], such as a more comprehensive, supply chain perspective on energy–export linkages [20], a comprehensive sustainability policy for overcoming the problems associated with production and consumption patterns and their impact on

the environment [94], etc. China aims at quadrupling per-capita GDP by 2020 compared to the year 2000. Without any energy and environmental policy measures, this tremendous economic growth would be accompanied with a quadrupling of primary energy consumption up to 6.3 billion ton of standard coal equivalents (sce) and energy-related CO_2-emissions of 13.9 billion ton against this background. Therefore, China needs to implement its sustainable development strategy into the quantitative context of the country's economic development and subsequent economic growth-related environmental problems. The country is urgently searching for a way to ease the negative implications of economic growth and has committed itself to achieve a level of 3.0 billion - ton sce primary energy consumption in 2020 [95]. However, how about the contribution of China's energy production to the total air emissions' impact? How about the different kinds of air emissions' contributions to the total air emissions' impact in the country? How about the interactions between China's economy, energy production and consumption and the related air emissions? Which factors will affect the realization of binding targets for energy conservation and emission reduction in the 12th Five-Year Plans (FYP)? How to deal with these issues in the 12th FYP? Therefore, it still needs to further explore the following issues so as to provide policy-makers with more comprehensive perspectives, including efficiency of energy production and use, energy security, energy mix, air emissions' impact from energy production and consumption, and the relationships between structures and scales of economy and energy and environment. These issues should be investigated through a systematic method so as to reveal the potential conflicts during China's fast economic growth against historical background. This paper aims to applying the emergy analysis method and several proposed indicators to investigate the relationships between China's rapid economic growth, energy production and consumption and the related impact of air emissions from 1995 to 2011 so as to provide a new perspective and some beneficial suggestions for policy-makers. Emissions' impact is quantified in terms of emergy; the corresponding indicators based on emergy and energy and money units are adopted to depict the interrelationships between GDP growth, energy production and consumption, and air emissions' impact. Detailed systematic indicators are examined from time serials, and temporal variation of indicators is explored to illustrate some characteristics of the Chinese economy. Finally, this paper discusses the corresponding issues and puts some related suggestions.

2. Methods

2.1. The interactions between economy, energy, environment and human being

As described in Fig. 2, energy production provides society with energy consumption so as to satisfy human's direct energy needs and drive economic growth. Economic development can satisfy human's material and psychological needs through paid service. Energy production and energy consumption can cause all kinds of air emissions to environment, which could have adverse impact on human health and economy. Consequently, economy and environment can influence each other. They can promote each other when keeping coordinative relationship; however, environment may hinder and even destroy economic development when resources exhaust and environment degrades. Finally, all these consequences will be imposed on human's wellbeing. Only by coordinating continuously the relationships between economy and energy and environment can human's wellbeing be supported and promoted permanently.

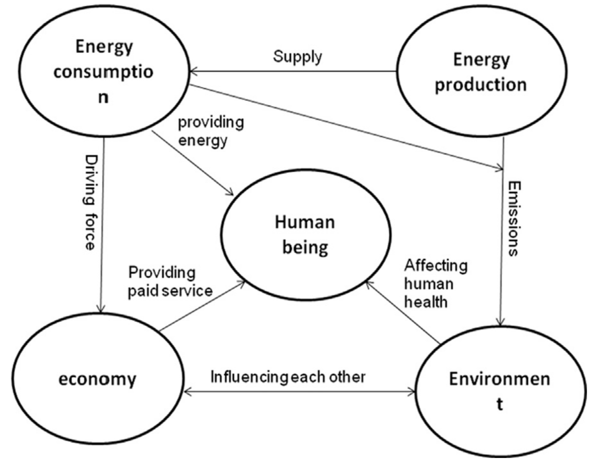

Fig. 2. The interactions between economy, energy, environment and human being.

2.2. Introduction of emergy analysis

Emergy analysis, founded by Odum, can fully integrate the values of energy, materials, and information in a common unit [33,34,96,97]. Emergy is expressed with the unit sej in which the solar energy is employed as the equivalent to measure different quantities and qualities of energy and materials. Transformity and other unit emergy values are proposed to determine the universal hierarchical position of the energy and materials. Therein, transformity refers to the emergy per unit of available energy output, and other unit emergy values stand for the emergy per unit of mass or currency output. Therefore, this method can evaluate the work previously done to make a product or service [33,34]. Although this method has been criticized since it appeared [98–102], it has been widely accepted as a feasible evaluation tool to assess different scale systems [32] with its gradual improvements in recent years [81,82,84,85,89,91,103,104].

Nowadays, four emergy baselines have appeared in emergy-related studies, including 9.44E24 sej/y [34], 9.26E24 sej/y [105], 15.83E24 sej/y [106], and 15.2E24 sej/y [103]. Results from existing studies of emergy intensity were converted to the 15.83E24 sej/y baseline in this study.

2.3. Quantifying air emissions' impact

Here, the method proposed by Zhang et al. [104] was adopted to quantify air emissions' impact. The emissions' impact includes two parts: one is ecological services which means that environment provides emergy to render emissions harmless [107] through diluting or degrading them to an acceptable concentration or state. The other is emergy loss caused by emissions, i.e. their harm to the ecosystem, people, and the economy. The method has been applied to assessing emissions' impact from China's steel industry [104], the sewage treatment system [77], ecological industrial systems [108], and China's economic activity [32], etc. It was briefly depicted as follows.

2.3.1. Quantifying ecological services

This emergy to absorb emissions' impact may be derived from the ecosystem which dilute or degrade the emissions to an acceptable concentration or state. The emergy of these ecological services may be determined from knowledge of the concentration and nature of the emissions, and the transformity of the relevant ecological services. Here we consider only environmental dilution of ecological services according to the reference [109]. As for

Table 1
Several air pollutants' accepted concentrations [112].

Pollutants' name	Acceptable concentration (mg/m^3)	Explanation
Dust	0.08	The concentrations in the first grade level in the corresponding environmental quality standards are regarded as the related pollutants' acceptable concentrations for the fact that they are the safest for humans and environment.
SO_2	0.02	
NO_2	0.04	

ecological service for diluting air pollutants, it can be counted as follows.

Firstly, the mass of air required to dilute each pollutant can be computed as follows.

$$M = d \times (W/c) - M_{air} \quad (1)$$

Where M is the mass of air for diluting one kind of air emission, unit: kg; M_{air} is the mass of discharged air from economic activity, unit: kg; d is air density, unit: 1.29 kg/m^3; W is the annual discharge amount of the corresponding pollutant from economic activity, unit: kg; c is the acceptable concentration from agreed regulations (See Table 1.).

Next, the kinetic energy of the air for diluting one kind of pollutant can be calculated using the formula $E = Mv^2/2$ (v refers to annual average value for wind speed in a country. Here, it is 2.24 m/s [110]). This energy is a measure of the wind energy needed to dilute the pollutant. Finally, the emergy of ecological services can be attained when the kinetic energy is multiplied by the wind energy transformity 2.45E03 sej/J [111].

2.3.2. Quantifying emergy loss

Emergy loss means the emergy contained in the ecological and economic loss. Therein, quantifying the ecological loss in terms of emergy requires making clear the corresponding loss of ecosystem components and self-organization [113] for it is represented by the potentially affected fraction or potentially disappeared fraction of species in the affected ecosystem [114]. The emergy of ecological loss can be attained through converting the output of a Life Cycle Impact Assessment Approach to a corresponding exergy loss or emergy input. Here the ecological loss was not considered due to lacking corresponding data. According to the references [115,116], the economic loss derived from air emissions' impact on human health can be described using disability adjusted life years (DALY) [114]. DALY represents the years of life lost and years lived disabled due to the emissions' impact, and it is based on an approach developed by the World Health Organization (WHO). The other details of DALYs see the Web of WHO.[1] DALYs can be further converted into ecological cumulative exergy consumption (ECEC) through the following approach [117].

$$C_j = m_j \times DALY_j \times \tau_{HR} \quad (2)$$

Here, m_j is the mass rate of emission of substance j; $DALY_j$ is the corresponding DALY value; τ_{HR} is the transformity of human resource, which is obtained by dividing total emergy budget of a nation or region by the total population of this country; C_j is the impact of emission on human health.

Value of ECEC is generally equal to emergy value for a given substance because they are both calculated through those same unit emergy values [118]. Then we can obtain the emergy value of emissions' impacts on human health in terms of ECEC. Table 2 lists several air pollutants considered in this work, the impact categories they belong to and corresponding DALY and ECEC values per million tonnes of emissions.

Table 2
Several air pollutants, immediate destination of emissions and impact categories ([116], corrected according to the emergy baseline 15.83 [106]).

Pollutants' name	Immediate destination of emissions	Impact categories considered	DALY/Mt of emissions	ECEC/Mt of emissions (sej/Mt)
SO_2	Air	Respiratory disorders	5.46E04	3.12E21
Dust	Air	Respiratory disorders	3.75E05	2.15E22
CO_2	Air	Climate change	2.1E02	1.20E19
NO_2	Air	Respiratory disorders	8.87E04	5.07E21

2.4. The corresponding indicator system

In order to evaluate the relationships between economy, energy and emissions' impact, a set of indicator system based on emergy, money and energy units was proposed, as follows.

Energy production efficiency (EPE, %): It refers to the efficiency of energy production process, and equals to the energy output divided by the energy input. Here it is the efficiency of energy conversion. The larger the indicator, the higher the production efficiency is.

Dependence degree of energy on foreign countries (DEFC, %): It is defined as the ratio of differences between imported energy and exported energy to domestic energy consumption. When DEFC ≤ 0, this kind of energy resource is self-sufficient; when DEFC > 0, the bigger the indicator, the higher the dependence of energy consumption on foreign countries is, and thus this kind of energy resource is more unsecure.

Energy consumption per unit GDP (ECPG, J/US$): It can be computed as the ratio of the total energy consumption to GDP. The larger the indicator, the lower the energy efficiency of economic activity is.

Percent of fossil energy (PFE, %): It stands for the share of fossil energy (here including coal, petroleum, natural gas and nuclear energy) in the total energy consumption. The bigger the indicator, the more unreasonable the energy structure is.

Emission impact per unit energy output (EIPEO, sej/J): It equals to the ratio of the emissions' impact to the related energy output. The bigger the indicator, the greater the environmental impact from energy production is. Meanwhile, this case also means the lower resource efficiency of energy production.

Emission impact per unit energy consumption (EIPEC, sej/J): It is defined as the ratio of the emissions' impact to the corresponding energy consumption. The larger the indicator, the greater the environmental impact from energy consumption is. And this also shows the lower energy utilization efficiency.

[1] Worth Health Organization (WHO). Metrics: Disability-Adjusted Life Year (DALY). http://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/index.html

Structure coordination degree (**SCD**): This indicator refers to structure coordination degree between energy, economy and environment, and it can be calculated as follows.

$$SCD_i = \frac{EPE_i}{EPE_0} \times \frac{ECPG_0}{ECPG_i} \times \frac{PFE_0}{PFE_i} \times \frac{EIPEO_0}{EIPEO_i} \times \frac{EIPEC_0}{EIPEC_i} \quad (3)$$

Here, EPE_i and EPE_0 refer to energy production efficiency in i year and reference year respectively; $ECPG_i$ and $ECPG_0$ mean energy consumption per unit GDP in i year and reference year respectively; PFE_i and PFE_0 mean percents of fossil energy in i year and reference year respectively; $EIPEO_i$ and $EIPEO_0$ refer to emissions' impact per unit energy output in i year and reference year respectively; $EIPEC_i$ and $EIPEC_0$ refer to emissions' impact per unit energy consumption in i year and reference year respectively; SCD_i refer to structure coordination degree between energy and economy and environment in i year.

This indicator is mainly affected by technical progress, industrial structure and energy mix. The bigger the indicator, the more coordinative the structures of energy and economy and environment based on reference year is.

Scale harmony degree (SHD): This indicator means the scale harmony degree between population, economy, energy and environment, and it depends on population scale, economic aggregate, quantity of energy consumption, and the total emissions' impact. The scale harmony is crucial for the sustainable social economy in future. The indicator can be computed as follows:

$$SHD_i = \frac{P_0 \times G_i \times EC_0 \times EI_0}{P_i \times G_0 \times EC_i \times EI_i} \quad (4)$$

Here, P_i and P_0 mean population in i year and reference year respectively; G_i and G_0 mean GDP in i year and reference year respectively; EC_i and EC_0 mean total energy consumption in i year and reference year respectively; EI_i and EI_0 refer to emissions' impact in i year and reference year respectively; SHD_i refer to scale harmony degree between population, economy, energy and environment in i year.

A bigger SHD value means more harmonious relationships between population, economy, energy and environment based on the reference year. Therefore, social economy could trend to be more sustainable in future.

2.5. Data resources

In this paper, data on China's GDP and per capita GDP came from China Statistical Yearbook [119]. The total amounts of energy production and consumption were mainly composed of coal, petroleum, natural gas, hydroelectricity, and nuclear power. Other energy sources were not considered due to lacking corresponding data in most years. Efficiency of energy conversion stood for energy production efficiency, and here we considered total efficiency, efficiency of electricity generation and heating by power stations, efficiency of coking and efficiency of petroleum refining. Energy-related data came from China Statistical Yearbook [120]. The air emissions mainly included CO_2, SO_2, NO_x and dust. Therein, emission factors of coal, petroleum and natural gas production came from the reference [121]. Here air emissions from hydroelectricity and nuclear power generation were not considered. NO_x emissions from coal consumption were mainly derived from end-use, power generation and coking. And the corresponding emission factors came from references [122–125]. NO_x emission factors of petroleum consumption came from reference [123]. NO_x emission factor of natural gas consumption came from reference [122]. Other air emission data of energy consumption came from references [120,126–129]. Because the historical data for emission factors were unavailable, it was assumed that the emission factors did not vary throughout the study period. Data on total waste gas discharge came from references [120,127–130]. And the value of annual average wind speed came from reference [110]. The transformity of wind energy is 2.45E03 sej/J according to reference [111]. The whole country, except Hongkong, Macao and Taiwan, was chosen as the analysis boundary.

3. Accounting

3.1. GDP and per capita GDP

As shown in Fig. 3, China's economy grew by 9.06 times by GDP or 8.02 times by per capita GDP from 1995 to 2011, with an annual growth rate of 15.52% by its GDP or 14.74% by its per capita GDP. The Chinese government has worked out a “Three Stage” development strategy to accomplish the modernization and establishment of a well-off society by 2050, and proposed to raise the GDP to the level of the middle-developed countries, with the per capita GDP reaching US$ 14,000–28,000 [131]. Therefore, China's per capita GDP will continue to increase with an annual growth rate of 2.92 – 4.72% in the next 40 years based on 2010.

3.2. Energy structure

3.2.1. Structure of energy production

As illustrated in Fig. 4, the total energy output increased by 1.47 times from 1995 to 2011, with an annual growth rate of 5.80% during the total study period. Therein, annual average percents in the total

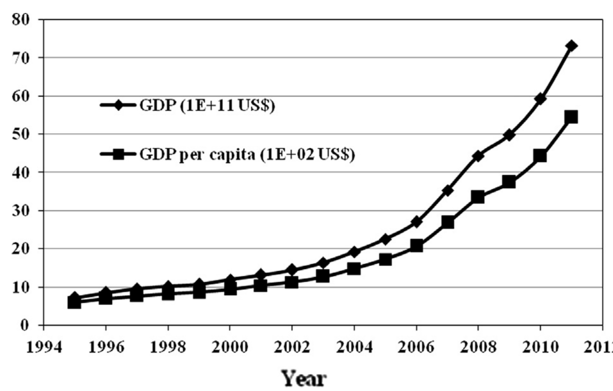

Fig. 3. Trends of GDP and per capita GDP of China during 1995–2011.

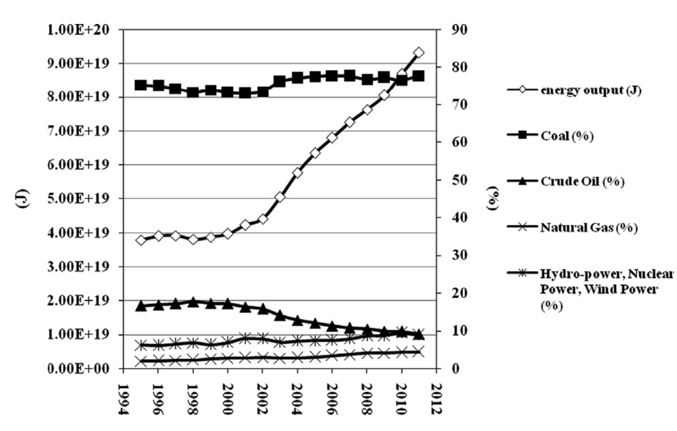

Fig. 4. Energy output and its structure in China during 1995–2011.

energy output were 75.67%, 13.84%, 3.02% and 7.47% for coal, petroleum, natural gas and other energy resources (hydro-power, nuclear power, and wind power) respectively, and total change rates in the total energy output were +2.50%, −7.50%, +2.40% and +2.60% for the four kinds of energy resources respectively during this study period. Therefore, China's energy output is still mainly composed of coal and petroleum. Meanwhile, coal continues to keep the leading position due to its abundant reserves and the relative price advantage whilst the share of oil production has declined obviously over time, which is still consistent with reference [93]. And other energy resources output has increased slightly in recent years.

3.2.2. Structure of energy consumption

As depicted in Fig. 5, the total energy consumption increased slowly before 2002, and then it rapidly rose after 2002. It was raised by 1.62 times, with an annual growth rate of 6.22% during 1995–2011. Therein, annual average percents in the total energy consumption were 73.71%, 20.92%, 2.91%, 2.23% and 0.23% for coal, petroleum, natural gas, hydroelectricity and nuclear power respectively, and annual change rates in the total energy consumption were −5.75%, +1.40%, +3.40%, +0.75% and +0.20% for these five kinds of energy resources during this study period. Obviously, the high share of coal in the energy output highlights its prominent position in energy consumption, and share of petroleum consumption is much higher that of the output, which means petroleum demand far exceeds the supply. While China's total energy consumption is still mainly composed of coal and petroleum, share of relatively cleaner energy resources has increased somewhat in recent years.

3.3. Air emissions' impact

3.3.1. Air emissions' impact from energy production

As given in Fig. 6(a), ecological service used to dilute air emissions fluctuated slightly from 1995 to 2002, and then rose obviously after 2002. It generally grew by 1.94 times, with an

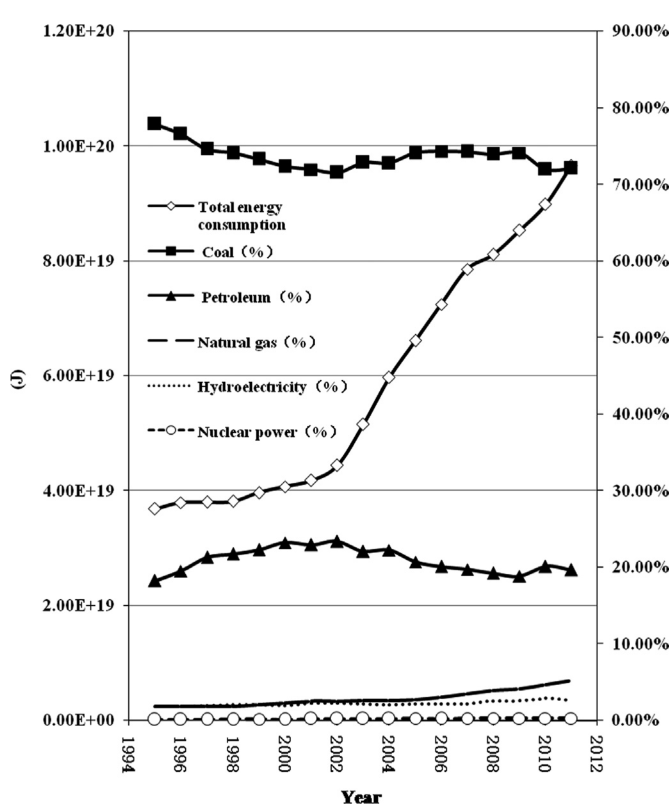

Fig. 5. Energy consumption and its structure in China during 1995–2011.

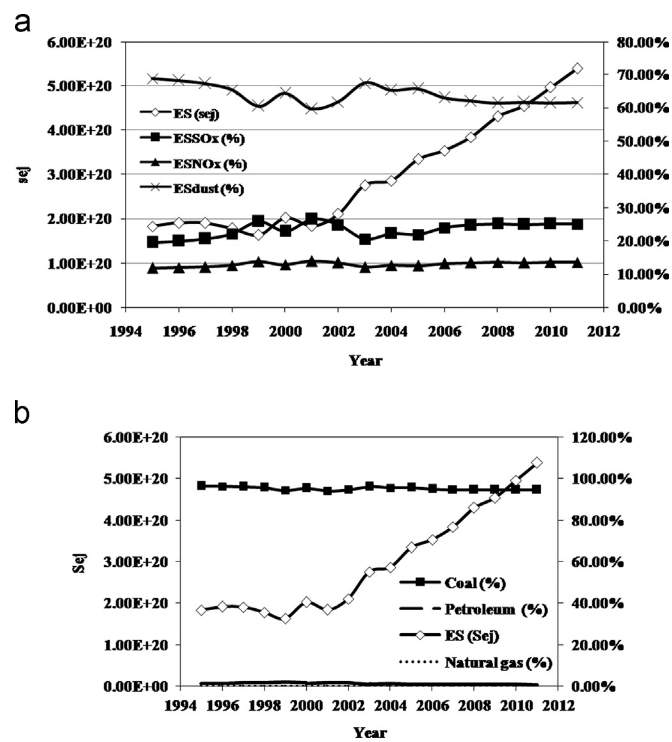

Fig. 6. Trends of ecological service used to dilute air pollutants (ES) from energy production and its structure in China during 1995–2011. (a) The structure of ES in terms of category of pollutants and (b) the structure of ES in terms of category of energy resources.

annual growth rate of 6.97% from 1995 to 2011. Therein, annual average percents in the total ecological service were 23.25%, 12.94% and 63.81% for SO_x, NO_x and dust respectively, and total change rates were +5.58%, +1.68% and −7.26% for the three air pollutants in the study period. In terms of category of energy resources, coal is the greatest contributor to the ecological service in the total study period (Fig. 6(b)). So a large amount of energy production driven by China's economic growth has placed increasing pressure on atmosphere environment especially after 2002; therein, the greatest contribution comes from dust, next from SO_x.

As shown in Fig. 7(a), emergy loss caused by air emissions from energy production fluctuated slightly from 1995 to 2001, and then climbed sharply after 2002. It rose by 2.95 times, with an annual growth rate of 8.96% from 1995 to 2011. Therein, annual average percents in the total emergy loss were 56.07%, 0.55%, 1.25% and 42.13% for CO_2, SO_x, NO_x and dust respectively, and total change rates were +17.86%, −0.02%, −0.21% and −17.63% for the four air pollutants in the study period. In terms of category of energy resources, coal was the greatest contributor to emergy loss before 1997; however, natural gas exceeded the contribution of coal after 1997 (Fig. 7(b)). These results show that air emissions from energy production have been increasingly seriously harming human health through affecting climate, respiration, skin exposure, etc. Therein, the greatest contribution comes from CO_2, next from dust. Shares of SO_x and NO_x are much smaller than that of CO_2 and dust in the total emergy loss, but they have direct and acute harm on human health in a short period. Meanwhile, while natural gas is a kind of relatively cleaner energy resource, the carbon emissions from its production should be emphasized in future.

As illustrated in Fig. 8(a), air emissions' impact from energy production fluctuated slightly from 1995 to 2002, and then increased obviously after 2002. It climbed by 2.95 times, with an annual growth rate of 8.97% during this study period. Therein, annual average percents in the total emissions' impact were 99.70% and 0.30% for emergy loss and ecological service respectively, and

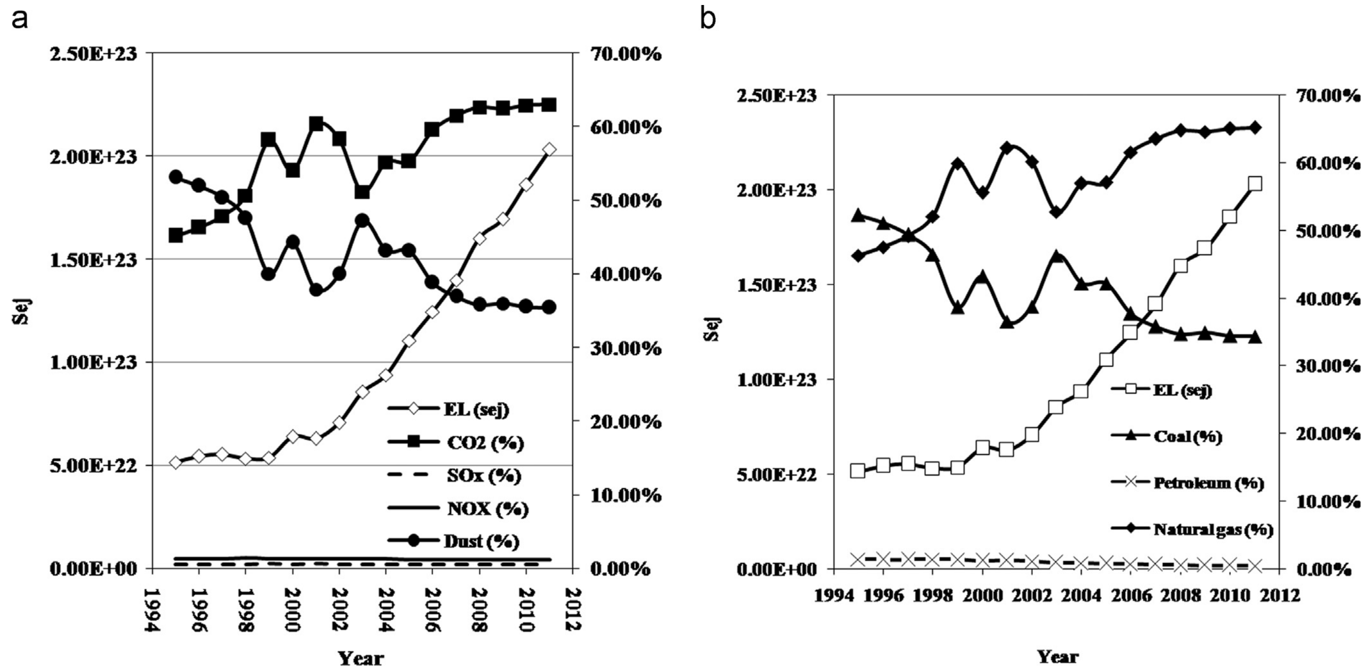

Fig. 7. Trends of emergy loss caused by air emissions (EL) from energy production and its structure in China during 1995–2011. (a) the structure of EL in terms of category of pollutants; (b) the structure of EL in terms of category of energy resources.

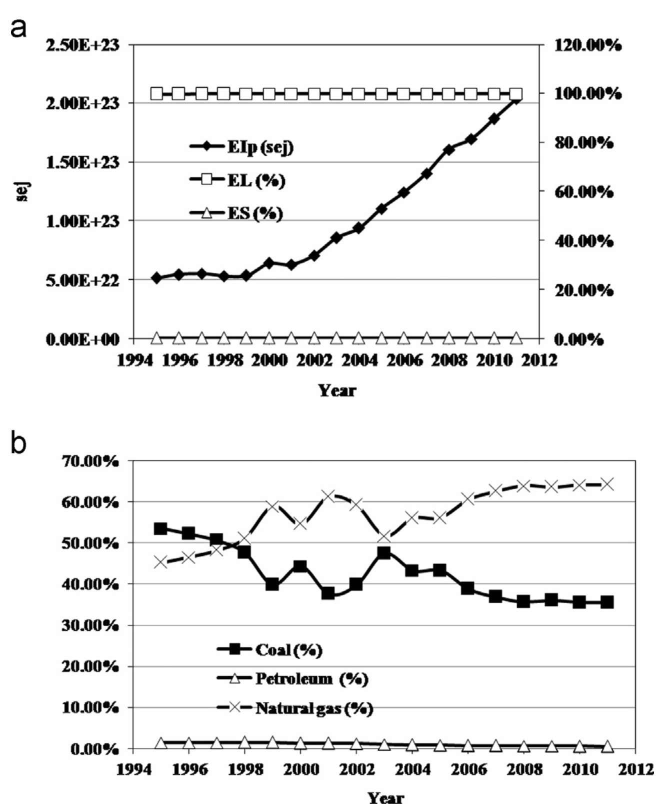

Fig. 8. Trends of air emissions' impact from energy production (EI_p) and its structure in China during 1995–2011. (a) the structure of EI_p in terms of category of pollutants and (b) the structure of EI_p in terms of category of energy resources.

total change rates were +0.09% and −0.09% for the two kinds of impact during 1995–2011. In terms of category of energy resources, coal had the greatest contribution to the total emergy loss before 1997; however, natural gas surpassed the contribution of coal after 1997 (Fig. 8(b)). Generally air emissions' impact on human health has absolute contribution to the total emissions' impact in the study period, in which natural gas has become the greatest contributor in recent years.

3.3.2. Air emissions' impact from energy consumption

As shown in Fig. 9, ecological service used to dilute air emissions from energy consumption rose in fluctuation by 25.58% and had an annual growth rate of 1.43% during the study period. Therein, annual average percents in the total ecological service were 59.69%, 24.67% and 15.64% for SO_x, NO_x and dust respectively, and total change rates were −3.55%, +22.33% and −18.78% for the three air pollutants respectively in the study period. These results show that air emissions from energy consumption have slightly rising pressure on atmosphere environment. Therein, the greatest contribution comes from SO_x, next from NO_x; however, the NO_x has increasing share in the total ecological service and should be more emphasized in future.

As depicted in Fig. 10, emergy loss caused by air emissions from energy consumption descended in fluctuation by 23.23% and had an annual decline rate of 1.64% from 1995 to 2011. Therein, annual average percents in the total emergy loss were 8.23%, 9.10%, 21.33% and 61.34% for CO_2, SO_x, NO_x and dust respectively, and total change rates were +10.99%, +3.37%, +27.59% and −41.95% for the four air emissions respectively in the study period. Air emissions from energy consumption have slowly decreasing impact on human health due to wide application of all kinds of dusting removal technologies; therein, the greatest contribution to emergy loss still comes from dust, next from NO_x. Furthermore, NO_x has increasing contribution to the emergy loss due to lacking effective control measures in this period.

As shown in Fig. 11, air emissions' impact from energy consumption decreased in fluctuation by 22.16% and had an annual decline rate of 1.55% during this study period. Therein, annual average percents in the total emissions' impact were 96.86% and 3.14% for emergy loss and ecological service respectively, and the total change rates were −1.40% and +1.40% for the two kinds of impacts from 1995 to 2011. Generally, air emissions' impact from

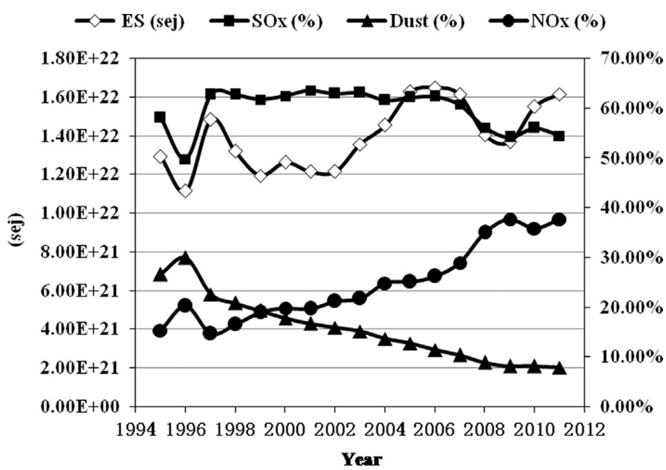

Fig. 9. Trends of ecological service used to dilute air pollutions from energy consumption and its structure in China during 1995–2011.

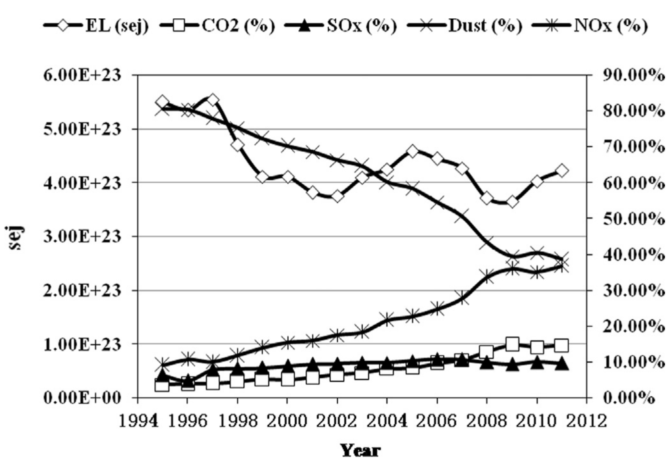

Fig. 10. Trends of emergy loss caused by air emissions from energy consumption and its structure in China during 1995–2011.

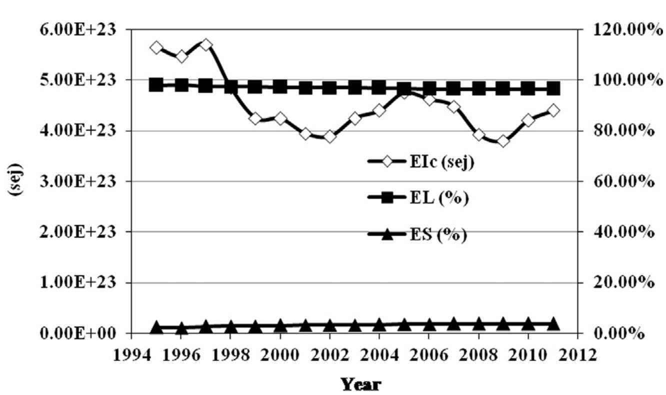

Fig. 11. Trends of air emissions' impact from energy consumption (EI_c) and its structure in China during 1995–2011.

energy consumption has decreased slightly, and air emissions' impact on human health is the main contributor.

3.3.3. Comparison between two kinds of emissions' impact

As illustrated in Fig. 12, total air emissions' impact from energy production and consumption descended by 4.38%, with an annual decline rate of 0.27% during the study period. Therein, annual average rates in the total emissions' impact were 81.75% and 18.25% for emissions' impact from energy consumption and energy production respectively, and total change rates were −23.35% and +23.35% for the two kinds of impact respectively during this study period. This shows that total air emissions' impact from energy production and consumption has been controlled to some degree. Although energy consumption still has the greatest contribution to the total emissions' impact, energy production has an increasing contribution to the total emissions' impact especially after 2002. And this should be mainly attributed to the rapid growth investment in infrastructure construction and real estate in recent years, which promoted rapid development of heavy industries, including steel, cement, and chemical and electricity industries [93].

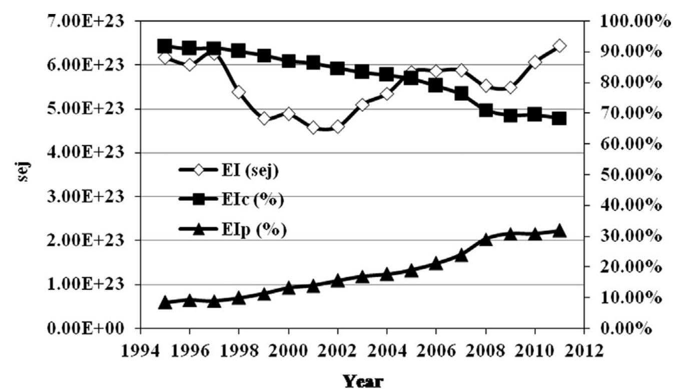

Fig. 12. Comparison between emissions' impact from energy production and energy consumption in China during 1995–2011.

4. Results and analysis

4.1. EPE

As shown in Fig. 13(a), production efficiency of electricity generation and heating by power stations grew by 13.64%, with an annual average efficiency of 39.03%, which is close to the research of Zhang and Wang [132]; production efficiency of coking rose by 4.79%, with an average efficiency of 96.18%; production efficiency of petroleum refining decreased by 0.69%, with an annual average efficiency of 97.07% during this study period. The total energy production efficiency was enhanced by 1.76% from 1995 to 2011, with an annual average production efficiency of 70.56%. It is found that production efficiency of coking and petroleum refining in China has attained a relatively high level. Compared with Japan (Table 3), production efficiency of electricity generation and heating by power stations in China is still lower and should be paid more attention to in future. The total energy production efficiency of China should belong to a middle level.

4.2. DEFC

As illustrated in Fig. 13(b), the total DEFC values were negative values before 1997, and then increased slightly in fluctuation after 1997, with an annual growth rate of 14.92% from 1997 to 2011. Therein, DEFC values of coal were negative values before 2009, and became positive values after 2009; DEFC values of petroleum rose rapidly in fluctuation from 7.59% in 1995 to 60.55% in 2011, with annual growth rate of 13.86% during the study period. And this phenomenon mainly lies in Chinese government's policies stimulating auto industry; DEFC values of electricity were negative values and had slight changes during this study period. These results show that China's coal production is completely self-sufficient and can support some export, China's petroleum

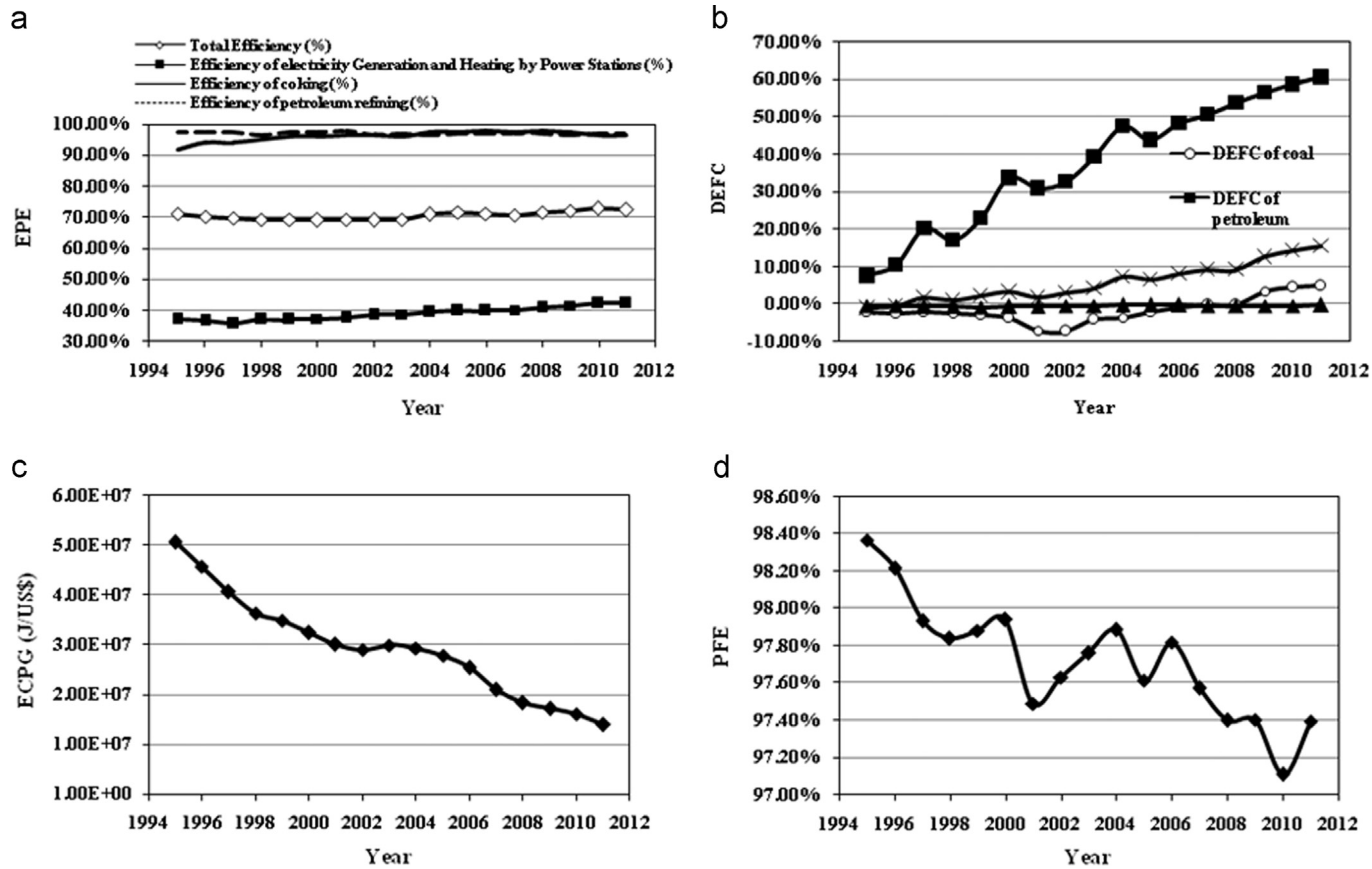

Fig. 13. Trends of EPE, DEFC, ECPG and PFE in China during 1995–2011. (a) EPE: energy production efficiency; (b) DEFC: dependence degree of energy on foreign countries; (c) ECPG: energy consumption per unit GDP; (d) PFE: percent of fossil energy.

Table 3
Comparison of gross coal consumption ratio for fossil-fired power plant between China and Japan (g sce/Kwh) [133].

Country	1995	2000	2005	2006	2007	2008	2009	2010	2011
China	379	363	343	342	332	322	320	312	308
Japan	315	303	301	299	300	297	294	294	294

production cannot satisfy its increasing petroleum consumption and this case leads to its growing dependence on international market, and China's electricity production is self-sufficient and has some surplus. Therefore, dependence of China's energy on foreign countries mainly came from the increasing petroleum consumption, which has surpassed the international warning line of 50% after 2007 [134]. China will have to require rapidly growing imports of oil and gas, which will become more sensitive to increases in motorization [135].

4.3. ECPG

This indicator decreased from 5.05E07 J in 1995 to 1.39E07 J in 2011, with an annual decline rate of 7.75% during the study period (Fig. 13(c)). Generally China's economy has greatly reduced its energy intensity; however, this pace of improvement still falls behind that of its economic growth rate in the same period. Though these improvements have been remarkable, the energy efficiency is still much lower than international advanced levels. For example, the energy intensity in 2006 was 2.5-fold higher than that of the world average and 7.2-fold higher than that of Japan [136]. China's current average energy efficiency is about 10% lower than that of the developed countries [131]. Meanwhile, there also existed some rebound effects in some years. For example, energy efficiency improvement in energy-intensive sectors derived from the industrial policies implemented had been offset by negative impact caused by low energy prices implemented in those sectors to some degree [137].

4.4. PFE

Generally this indicator declined in fluctuation by 1.00% during this period (Fig. 13(d)). These results show that China's energy mix has not been obviously improved although China's central government has taken many related measures [134]. Therefore, China's economy will continue to depend on fossil energy greatly in a long period, and it will still confront huge pressure from energy conservation and emission reduction in future.

4.5. EIPEO

This indicator generally increased by 60.00%, with an annual growth rate of 2.98% during the total study period (Fig. 14(a)). This phenomenon should be mainly attributed to rapid growth of energy output and insufficient air pollution control measures in the process of energy production, and thus these negative impacts exceeded the active role derived from improvement of energy production efficiency in the same period (Fig. 13(a)). Guan et al. [138] pointed that China's production-related CO_2 emissions will increase another three times by 2030 relative to the 2002 level. Therefore, production-related emissions should be more emphasized in future.

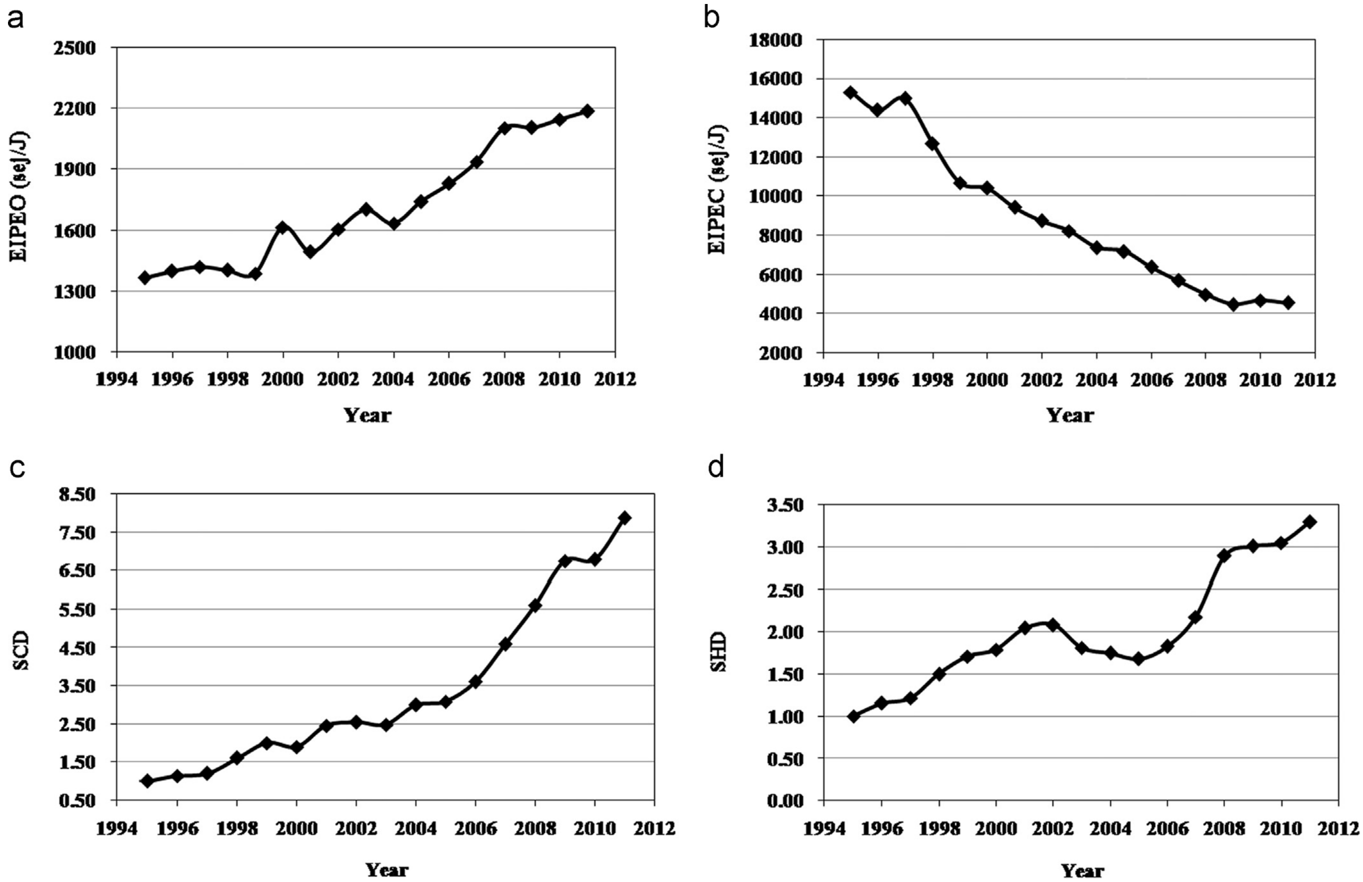

Fig. 14. Trends of EIPEO, EIPEC, SCD and SHD in China during 1995–2011. (a) EIPEO: emissions' impact per unit energy output; (b) EIPEC: emission impact per unit energy consumption; (c) SCD: structure coordination degree; (d) SHD: scale harmony degree.

4.6. EIPEC

Generally this indicator descended by 70.32%, with an annual decline rate of 7.31% during the study period (Fig. 14(b)). These results show that air emissions intensity from energy consumption has been reduced greatly, which is mainly derived from energy conservation and emissions reduction- related policies implemented in recent years. However, due to the high share of coal in energy consumption in the next 50 years, air pollution control from coal utilization will be still a high priority for this country [139].

4.7. SCD

This index increased slightly in fluctuation due to economic structure worsening and ineffective environmental management instruments during 1995–2005, and then rose obviously after 2005 due to China's central government taking some measures to optimize economic structure and strengthen environment supervision and management in the 11th FYP [140]. Generally it increased by 6.86 times and had an annual growth rate of 13.75% in this study period (Fig. 14(c)). Therefore, the relationships between economic growth rate, energy efficiency and emission intensity in China have become relatively coordinative especially after 2005. However, this improvement was still slightly falling behind the pace of China's economic growth in the same period.

4.8. SHD

Generally this index rose by 2.29 times, with an annual growth rate of 7.73% in this study period (Fig. 14(d)). This shows that the relationships between China's population, economic aggregate, total energy consumption and air environment protection have become relatively harmonious based on the year 1995. However, due to the improvement of scale harmony degree still far falling behind the economic growth rate, the absolute decoupling phenomena had not happened in China during this period.

5. Discussion

Several indicators based on energy, emergy and monetary units were put forward to depict the relationships between China's economic growth, energy production and consumption, and the corresponding air emissions' impact during 1995–2011. Uncertainty analyses show that our results basically represent the trends of overall energy production and consumption and related air emissions' impact of the country during the study period (see SI-1), and can provide the related policy implications for adjusting the relationships between economic growth, energy production and consumption and air emissions' impact.

It will be more difficult to further increase production efficiency of coking and petroleum refining in future because their efficiency has exceeded 96%. Maybe enhancing the total energy production efficiency should mainly depend on further raising production efficiency of electricity generation and heating by power stations in future. The related measures include (1) optimizing electricity structure, such as further closing down small-scale thermal power plants and constructing large-scale ones; (2) prioritizing developing large-capacity, highly efficient, and low emissions power generation technologies using direct combustion of coal, such as supercritical power generation technology, ultra-supercritical power generation technology, etc; (3) accelerating

power grid update, optimizing power grid operation and management, improving power distribution network so as to reduce loss during the course of power transmission and transformation [141].

Due to abundant fossil energy reserves (especially coal) and the related price advantage, China's energy consumption structure will not change obviously in a short period. This case will continuously endanger air environment quality especially in those areas with concentrated heavy industries and transportation in future. Moreover, this situation could be aggravated due to lacking sufficient effective air pollution control measures for small particulate matter, SO_x, and NO_x in the fields of production and transportation. So it is very urgent for China's governments at all levels to further improve regional industrial planning according to the local air environmental capacity. Therein, it is the key to carry out local functional zoning and choose proper industrial types and scale during the course of region planning. At the same time, research and development (R&D) of efficient and affordable air pollution control technique and equipment is urgent for mitigating China's air pollution in future.

Most of the energy resources in China are self-sufficient even somewhat surplus; however, China's petroleum output cannot far meet its growing consumption, which is being seriously challenging China's energy security. In order to mitigate this tense situation, the fundamental way may lie in adjusting Chinese people's obsession with cars besides R&D of alternative energy for oil and new energy vehicles. To this end, on one hand, China's governments should restrict the number of the private cars through further enhancing taxes on car sales and fuel oil consumption. On the other hand, China's governments should strive to develop public transportation so as to convenient for people to travel.

Air emissions from energy consumption needs to be further controlled because it is still the largest contributor to the total emissions' impact; meanwhile, air emissions from energy production should be more concerned due to its increasing share in future. Therein, dust and CO_2 from China's energy production, and SO_x and dust from China's energy consumption should be specially emphasized because they have prominent impact on air environment and human health. While natural gas is a kind of relatively cleaner energy, the air emissions from its production should be also emphasized because it has the largest contribution to emissions' impact from energy production, including improving its quality, enhancing its efficiency, etc.

Energy conservation and emissions reduction-related policies have not played an obvious role in the energy production field. Therefore, how to implement effectively those policies in energy production field depends on the synergistic effect (maximizing the positive effect and minimizing the negative impact) of many comprehensive countermeasures, such as technologies reform, cleaner production audit, energy conservation assessment, environmental impact assessment, and related supervision and management measures, etc.

In order to quantify effect of different indicators or factors on the two indices SCD and SHD, here we adopt the Logarithmic Mean Divisia Index Method to carry out a decomposition analysis of the two indices (See SI-2.). It is found that EIPEO has the largest negative impact on SCD, and ECPG has the biggest positive contribution to the index during 1995–2011. Energy consumption has the largest negative impact on SHD, and GDP has the positive contribution to the index during this period. Generally technical progress has promoted structure coordination between economy, energy and emissions in China. Meantime, the scales of population, economy, energy and emissions have become relatively harmonious during this period. Due to scales' harmony degree far falling behind structure coordination degree in the same period, the active role played by technical progress has been greatly offset by rebound effect of energy use growth in China [142].

In summary, the main obstacles affecting the sustainability of China's economy come from rising air emission intensity of energy production, unreasonable energy mix and excessive growth of energy consumption. Therefore, optimizing energy mix, adjusting the related industrial structure, strengthening air emissions control for energy production, and properly restraining energy consumption will be still the main tasks of China's governments at all levels in future. In order to address these issues, the following countermeasures are proposed: (1) Further pushing forward technological innovation. Firstly, China should actively push forward the corresponding R&D of new energy-saving technologies and products. Secondly, the country should strive to develop alternative energy technologies for mitigating air emissions' impact from coal consumption. Therein, renewable energy (RE) technologies should be further promoted. In the near and medium term, China's government should mainly focus on hydropower and wind power due to their more mature technology and lower cost. Biomass power should also be well developed if its resources can be guaranteed. In the long-term, it will be feasible to develop vigorously solar power, geothermal power and ocean energy with maturity of relevant technologies [143]. Due to great contribution to energy consumption and emissions, RE technologies for transportation electrification should be also developed [144]. Thirdly, the country should further promote the spreading of new energy and clean energy technologies, including improving and extending the electricity infrastructure, harmonizing the relationships between wind power systems and thermal power system [145], etc. Finally, improving the energy transportation system is also necessary for rational distribution of energy between different areas and reduction of energy loss. (2) Strengthening energy conservation and emissions reduction in process of production. Firstly, China should accelerate closing down of backward production capacity, especially in coal, iron and steel, cement, and coking industries. Secondly, the country should strive to promote energy saving and environmental protection in heavy industry, construction, transportation, public institution and some key projects. Thirdly, the country should improve energy saving related legal laws and standards, and cultivate the related market rules so as to popularize advanced energy saving technologies and products. (3) Speeding up adjusting industrial structure. Firstly, China should promote industrial structure transformation from high energy consumption heavy industries to energy saving technology-intensive industry, restrain development of industries heavily depending on oil import, and encourage developing knowledge-intensive industries. Secondly, the country should carry out structure optimism inside industry, including accelerating developing low energy consumption industries (such as light industry, machine building industry, high-tech industries, and agricultural product processing industries, etc.), discarding high energy consumption equipments and encouraging enterprises use clean energy resources. (4) Optimizing energy mix. And this needs to accelerate optimizing and adjusting energy consumption structure so as to gradually decrease coal share. Firstly, China should strive to develop clean coal technology so as to avoid or reduce environmental pollution from coal developing and processing, including large-scale coal gasification, direct- and indirect coal liquefaction and the exploitation of the coal polygeneration system, etc. Secondly, the country should further promote exploration and development of oil and natural gas resources so as to stabilize domestic oil output, promote fast growth of natural gas output, and boost development of unconventional oil and gas resources, such as coal bed methane, shale gas, etc. Thirdly, China should also continue to expand the international oil and gas market so as to reduce the serious negative environmental impact

derived from coal consumption in the short period. (5) Promoting the multifarious energy developing pattern, including constructing safe and efficient coal mines, pushing forward integrated use of coal resources, developing relatively cheap and efficient nuclear energy based on safety, actively developing new energy resources (Such as solar energy, wind energy, biomass energy, and geothermal energy.), etc. [146]. (6) With fast increase of residential sector's energy consumption, energy-saving in ordinary life should be further emphasized, such as popularizing energy-saving domestic appliances, implementing differential electricity prices based on regional average levels of per capita electricity consumption, etc. (7) Coordinating energy and environment-related policies with economic structure adjustment-related ones. Nowadays, there still exist some conflicts between these policies, which have weakened the expectant effect to some degree. For example, China's government would like non-energy-intensive sectors, like the service industry, to play a greater role in economic growth than previously in the 11th five-year-plan period, but market forces have driven the changes in the economic structure in the opposite direction. Statistical data show that the value-added of tertiary industry accounted for about 40% of GDP since 2005, down from 41.5% in 2002 [134]. Reducing SO_2 emissions with the use of desulfurization equipment raises energy use and CO_2 emissions. Improving energy security by reducing oil imports may mean a greater use of domestic coal, which worsens the local air pollution. These complex linkages are embedded in the bigger national objective of raising living standards for all regions, i.e. policies to address the energy and environmental issues should be consistent with the national economic goal. Therefore, all these related policies should be planned and designed systematically so as to realize the expectant goal.

The proposed indicators EPE stands for energy production efficiency, DEFC reflects energy security, ECPG gives energy intensity of economic activity, PFE depicts energy mix, EIPEO describes emission intensity of energy production, and EIPEC shows emission intensity of energy consumption, the index SCD embodies structure coordination degree between energy and economy and emissions, and finally the index SHD reflects scale harmony degree between population, economy, energy and emissions. They can form a set of useful indicator system to evaluate the relationships between economy, energy and environment for one country or region in different years, and then provide beneficial suggestions for decision-makers.

6. Policy implications for the 12th FYP

As shown in Table 4, the structure coordination degree and scale harmony degree in 11th FYP is obviously superior to those in the other two FYPs. Compared with the general levels of 11th FYP, the two indices in the first year of 12th FYP was inferior although the economy still kept fast growth. Therefore, energy utilization efficiency and emissions from energy production should be further emphasized so as to optimize industrial structure. Therein, the exploitation and utilization of RE sources is in an urgent need for China's current energy mix adjustment, energy conservation and emissions reduction, and rational control of total energy consumption [147], which may be superior to efficiency improvement, nuclear power, and CO_2 capture and storage (CCS) [143]. China's government has formulated and implemented an array of major policy for RE and energy efficiency and some progress has been made [148]. However, due to the higher cost than traditional energy resources at present, it is crucial to provide appropriate policy, funding and technical support to RE to ensure a more positive effect on energy conservation and emissions reduction [143], including promoting RE technology innovation and the corresponding demonstration and diffusion [149–152], formulating and revising the technology standards of RE and relevant evaluation systems [153], improving the relevant power grid system and strengthening the responsibility of power grid companies in RE use [150], innovating market mechanism for application of RE [148,150–154], integrating RE target into upper level of national energy and emissions reduction targets [150], ensuring the consistency of the central and local policies and different governmental departments [148,151,153,154], strengthening supervision from a third part in implementing RE projects [150,153], promoting the use of energy service companies (ESCOs) and energy performance contracting [148], improving the energy efficiency obligation (EEO) scheme [148], exploring a perfect co-management mechanism that government, market and public are all involved in [152], publishing the policy on the resource survey of RE so as to provide more data for the development of RE [153], making clear the development planning of RE [153,155], and promoting the international cooperation in the RE field [151,156]. Furthermore, the interactions between energy efficiency, energy mix and total energy consumption should be specially paid more attention to so as to promote scale harmony. In order to realize the targets of energy-saving and emissions reduction in the 12th FYP, the synergies between economic growth and targets of energy conservation and emissions reduction should be promoted. In other words, the active roles and negative effects of one policy or measure should be considered simultaneously. Otherwise, the active roles could be offset even surpassed by the negative effects. As far as some binding targets in the 12th FYP are concerned, reducing energy intensity and emissions intensity through technical progress are far insufficient due to side-effects and/or rebound effect rooting in scale increase. As necessary supplements, the total amount control for fossil energy consumption (especially coal) and total emissions control for main pollutants should be implemented synchronously. The total quantity control can be initiated through administrative measures at early stage, and then economic means should become main measures in the later period so as to cultivate total quantity trading market, such as energy price reforming, fossil energy consumption trading, environmental taxes reforming, emissions trading, etc. Therein, improving the energy demand side management may be one of effective measures [157]. Meantime, China should further strengthen acting locally and supervision and management when implementing national targets. Therein, it is very urgent to integrate capacity building into energy conservation and emission reduction-related policies and take a systematic approach to equip local officials with the newest scientific knowledge, policy developments, and necessary capacities for addressing climate change and environmental issues [158]. In order to coordinating the relationships between economy and energy and environment, reforming the current institutional approaches is also necessary [159], including further enhancing top-down decision making and management levels, strengthening monitoring and assessment of projects; promoting coordination between government bureaus, sufficiently considering local interests, etc. Finally, enhancing responsibility of local governments is the ultimate guarantee measure, such as improving assessment

Table 4
Comparison of the two indices in different FYPs.

Period	Growth rate of SCD (%)	Growth rate of SHD (%)	Growth rate of GDP (%)
9th FYP	13.58	12.35	10.48
10th FYP	10.33	−1.26	13.51
11th FYP	17.02	12.67	21.29
12th FYP (2010–2011)	15.93	7.87	23.59

systems for local officers' achievements, and strengthening the administrative accountability system. Only placing environmental and energy concerns on par with economic growth can China truly solve the conflict between economic growth and energy resource scarcity and environmental degradation.

7. Concluding remarks

(1) China's basic energy mix is still mainly composed of coal and petroleum during 1995–2011; therein, increasing petroleum import will continue to threat China's energy security in future.
(2) The total air emissions' impact has been controlled to some degree in the study period. Therein, energy consumption has the greatest contribution to the total air emissions' impact whilst energy production has an increasing share. In terms of energy category, coal contributes the largest to emissions' impact from energy consumption, and natural has become the biggest contributor to emissions' impact from energy production in recent years. Air emissions' impact on human health is the largest contributor to the total emissions' impact.
(3) Energy conservation and emissions reduction-related policies have played an active role in the field of energy consumption, but they have no obvious effect on energy production during the study period.
(4) Generally the relationships between economy and energy and environment in China have become relatively improved; however, the absolute decoupling phenomenon has not appeared during the study period.
(5) In order to realize the targets in twelfth FYP, the synergetic strategy based on efficiency and total quantity control should be adopted.

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Appendix A. Supplementary material

Supporting information associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2014.07.002.

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